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TECHNICAL REPORT FOR 1992-93 FOR PROJECT 3210B

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Cooling and Trapping of Neutral Atoms

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1. Quantization of Atomic Motion. Atoms can be easily cooled to KE to below 0.2 MHz (≈10 μK), below the light shifts in a weak standing wave. At low excitation rates, an optical standing wave may be viewed as producing a sinusoidal potential. Atoms are then confined in the $\lambda/2$ space between the planes of the standing wave, but have a deBroglie wavelength $\approx\lambda/10$ or more. Thus their motion is quantized by the light field. We have evidence of this quantization of motion from direct rf spectroscopy of the vibrational states in the wells. The position of the rf peaks do not correspond to the calculated energy intervals, and do not shift with laser parameters as expected. However, the simple picture that we are driving stationary states in a static potential may be inappropriate for these experiments.

2. Transient Effects in Laser Cooling We have carefully studied some transient effects that produce both cooling and heating, but often with the opposite detuning from that of steady

state. The time scale for these effects is set by the optical pumping (OP) rate to a ground state not coupled by the laser field. The combination of such OP processes and the conservative light shift potential can lead to sub-Doppler transient cooling.

Atoms that enter the standing near a node experience the optical force until they are optically pumped to an uncoupled state, which is more likely to happen at high light intensity, near an antinode. For $\delta > 0$ this means higher potential energy and thus lower KE, and conversely for $\delta < 0$. We have made both classical and quantum mechanical studies of these experiments, and both of these agree very well with one another and with the data.

<u>3. Cooling Experiments in Helium.</u> We are studying light forces on atoms in the regime where the atomic transition linewidth γ, and the recoil frequency $\omega_R \equiv \hbar k^2/2M$ are comparable. To do this we have chosen two transitions from the triplet helium metastable 2^3S_1 state (He*), one at $\lambda = 1.083\ \mu m$ to the 2^3P manifold and the other at $\lambda = 389$ nm to the 3^3P manifold. The ratio ω_R/γ is $\cong 0.05$ for the 2^3P state but 0.4 for the 3^3P state. Thus the infrared experiments will be in the ordinary domain of laser cooling where $\omega_R/\gamma \ll 1$ and can be used to characterize the apparatus, while the uv experiments will provide a test for various models of laser cooling in this domain.

We have built and tested a source of He* that produces $\approx 10^{14}$ atoms/s-sr. The $\lambda = 1.083\ \mu m$ light is produced by a highly developed, home-made, diode-pumped LNA laser. We have used the mechanical Hanle effect on the $J = 1 \Rightarrow 1$ and the $J = 1 \Rightarrow 2$ transitions[6] to map and calibrate the $\vec{B}$ field directly along the path of the atoms that participate in the experiment with an accuracy in the mG range.

4. Cooling Atoms with Diffuse Light. Use of diffuse light for deceleration of a sodium beam has been studied and demonstrated, and we are working on such experiments with diode lasers in Rb. The obvious advantages of such a beam slowing technique is that it is relatively insensitive to alignment and laser spectral width and stability, and that it requires no counterpropagating beam of light through an interaction region. Diode lasers offer distinct advantages for such experiments for many reasons; e.g., it's easy to have different frequencies present simultaneously.

5. The Simplest Cooling Schemes. In all cases of SDLC the role of coherences between ground state sublevels, established by either Raman or Zeeman processes, is of paramount importance. The next natural question is what is the simplest possible atomic level structure that would admit SDLC. A two-level $J = 0 \Rightarrow 0$ transition will not work, but four level $J = 1 \Rightarrow 0$ or $1/2 \Rightarrow 1/2$ transitions will work ($J = 0 \Rightarrow 1$ will not work). We have studied SDLC in both the 28% abundant ^{87}Rb isotope and metastable He that have $J = 1 \Rightarrow 0$ transitions that are ideal for studying this simplest case of SDLC. This case can be easily studied theoretically because the Hamiltonian is particularly simple.

We have studied SDLC in a $J = 1 \Rightarrow 0$ transition in both a circularly polarized standing wave with a weak transverse magnetic field, and in a polarization gradient with a strong magnetic field (strong means Zeeman shifts larger than the light shifts). Although our models predict cooling to $v = 0$ in both cases, the detailed nature of the cooling mechanism in these two schemes is quite different. In weak B fields, the optical field determines the quantization axis and the natural choice for a basis is the set of eigenstates of the light shift operator. In strong B fields the eigenstates of the Zeeman operator form the basis set, and qualitatively new effects appear.

6. Quantum Theory of Laser Cooling. The semiclassical theory of laser cooling that uses the Fokker-Planck equation to find the momentum distribution is inconsistent in the regime of very low atomic kinetic energies. We have extended the $J = 1/2 \Rightarrow 3/2$ fully quantum mechanical calculation of Castin and Dalibard from their simplest polarization gradient case to the higher angular momentum states corresponding to our experiments in Rb. Such atoms move in a manifold of sinusoidal potentials arising from the different optical coupling strengths and well defined bands can't be formed.

We applied this to magnetically induced laser cooling where both laser beams have the same circular polarization and thus the different m states are not coupled by optical transitions. Narrow, low-lying, bound bands can now be formed and laser cooling is depicted as optical pumping among the quantized vibrational levels or external states of motion, much like traditional optical pumping among the internal atomic states. Proper choice of laser parameters favors pumping toward lower kinetic energy states.

7. Monte Carlo Wave Function Calculations. The recent discovery that the density matrix evolution can be simulated by Monte Carlo techniques has provided a powerful new tool for a variety of atomic calculations. We have developed a computer code for this formalism to treat Doppler cooling, polarization gradient cooling, and magnetically induced cooling in 1-D optical molasses for the angular momenta appropriate for He*. This formalism provides sub-recoil resolution of the calculated momentum distribution function even when the atomic wavefunction is discretized on a one recoil spaced grid. We have made considerable progress on a detailed comparison of these two methods with the semiclassical theory for the case $\omega_R/\gamma \sim 1$.

8. Beam Profile Flattening. We discovered a novel technique to make a Gaussian laser beam profile spatially flat. We exploit the angular dependence of the transmission of an etalon to tailor the spatial profile to the desired form. A converging or diverging laser beam is transformed into the familiar ring pattern when it passes through an etalon, and the central bull's eye corresponds to a spatially dependent transmission that can be used to shape the beam's intensity profile. A simple analysis shows why our method works so well, and how an etalon could be tuned to give the optimum results at all wavelengths. This technique has enormous advantages over other methods.

9. Optical Feedback into Diode Lasers. Optical feedback can cause enormous effects in both the operating frequency and the linewidth of diode lasers. We have adapted the standard formulae

used by optical communication engineers and applied them to diode lasers used for atomic spectroscopy. Very tiny amounts of light, such as from diffuse reflection from a distance surface, are sufficient to wreak havoc with a carefully selected and tuned laser. The sensitivity to feedback is ~10^4 time larger than a dye laser and can drive the laser into multiple modes. Optical feedback also has a enormous effect on the laser's frequency. For changes as small as 1 μm out of 25 cm to a reflecting surface, the laser frequency can change by 25 MHz, even for diffuse reflection. Thus vibrations or thermal motion of a surface illuminated by a stray reflection can cause huge detrimental feedback effects.

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RE: N00014-90-J-1012

Dear Dr. Reynolds:

Enclosed please find three copies of the Technical Report for Dr. Harold Metcalf's above referenced grant.

If you have any questions, please contact me at 516-632-9039.

Sincerely,

Barbara Harris

Barbara Harris
Associate for Sponsored Programs

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